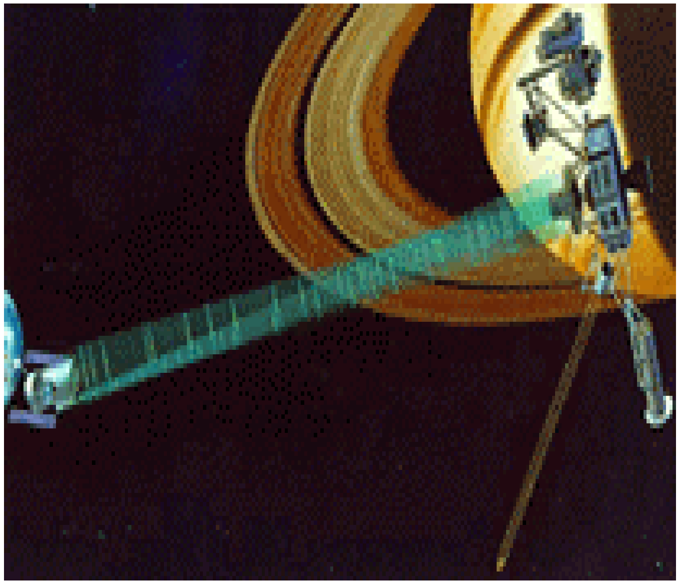


September 22, 1999

Deep Space Acquisition, Tracking, and Pointing Technologies for Optical Communications

Shinhak Lee

James W. Alexander

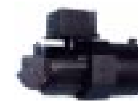
Gerry G. Ortiz

Jet Propulsion Laboratory
California Institute of Technology

Outline

- Introduction/Background
- Pointing Requirements
- Technologies for Deep Space
- Key Technology Developments
- Summary

Benefits and Challenges of Optical Communication



Benefits

- High data rate
- Small, lightweight terminals
- Low power
- EMI insensitive

Challenges

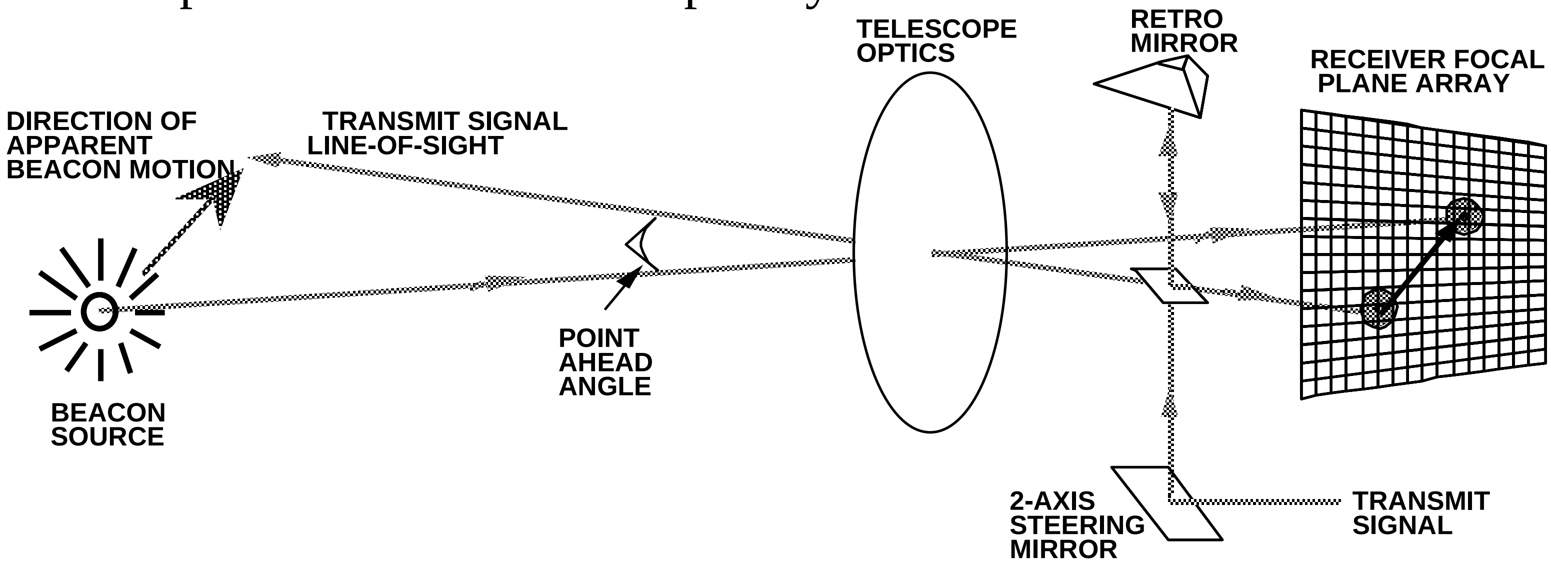
- Accurate beam pointing
- Background light sources
  >>Sun, Moon, Planets
- Optical alignments
- Atmospheric attenuation

Optical Comm Background

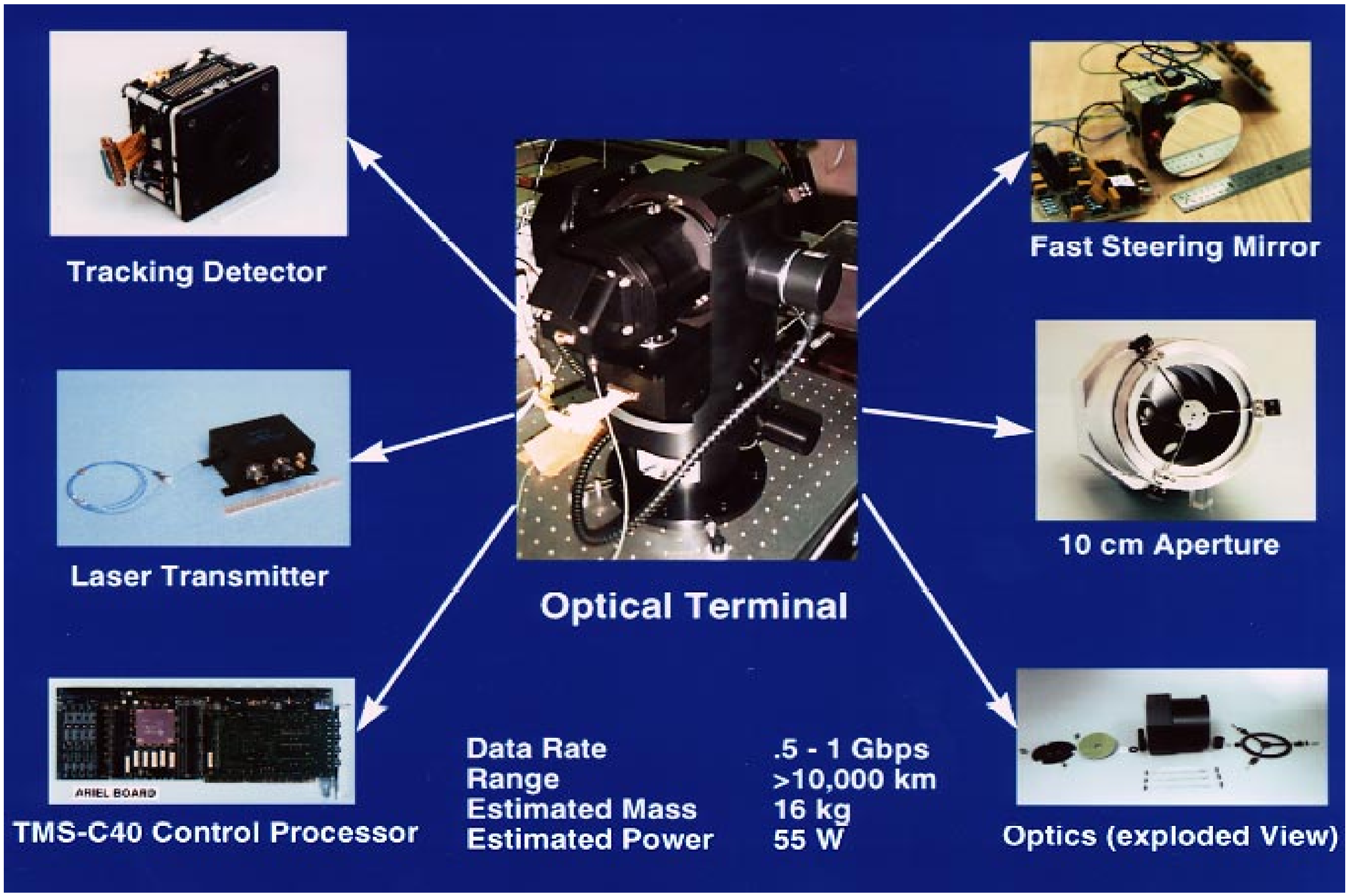
- JPL program started in 1979
- Includes spacecraft and ground technologies, systems, infusion planning, and system-level demonstrations
- Developed an Optical Comm. Demonstrator (OCD)
  - Laboratory-qualified functional model of a flight terminal
- Conducted a number of system-level demos
- Installing an Opt. Comm. Telescope Lab. (OCTL)
- JPL has responsibility for all NASA applications of optical comm

Opt Comm Demonstrator Concept

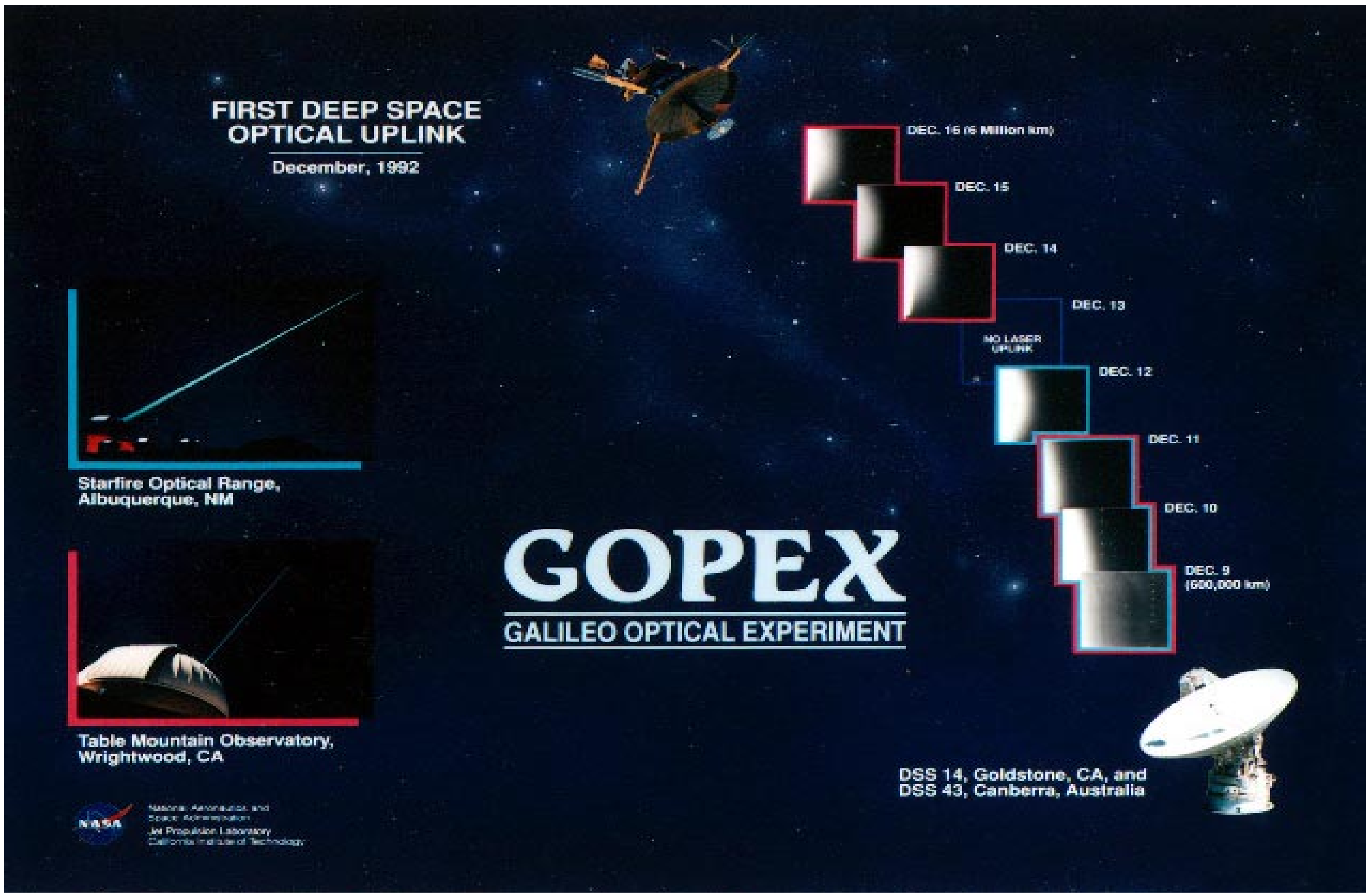
- Uses single steering mirror and single tracking detector array to accomplish beacon acquisition, tracking, XMT/RCV co-alignment,and transmit-beam point-ahead
- Fiber-coupled laser transmitter removes heat from optics area
- NASA-patented “minimal-complexity” architecture



Lab-OCD Realization



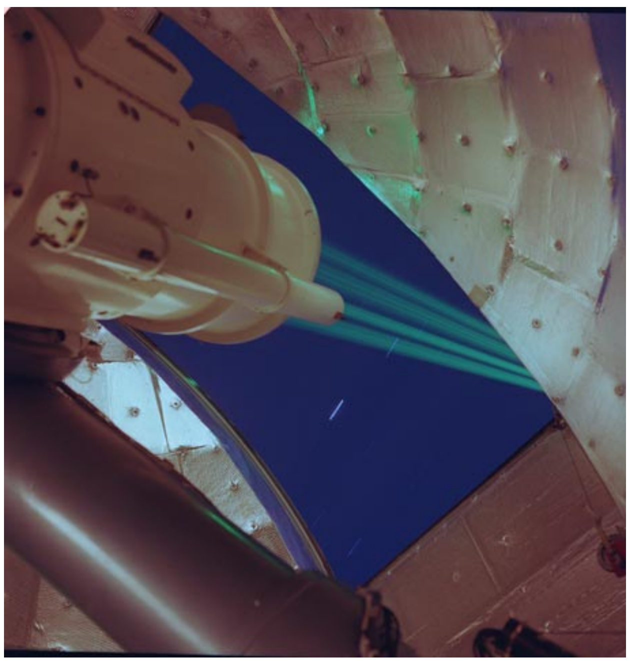
Past Opt. Comm. Demonstrations



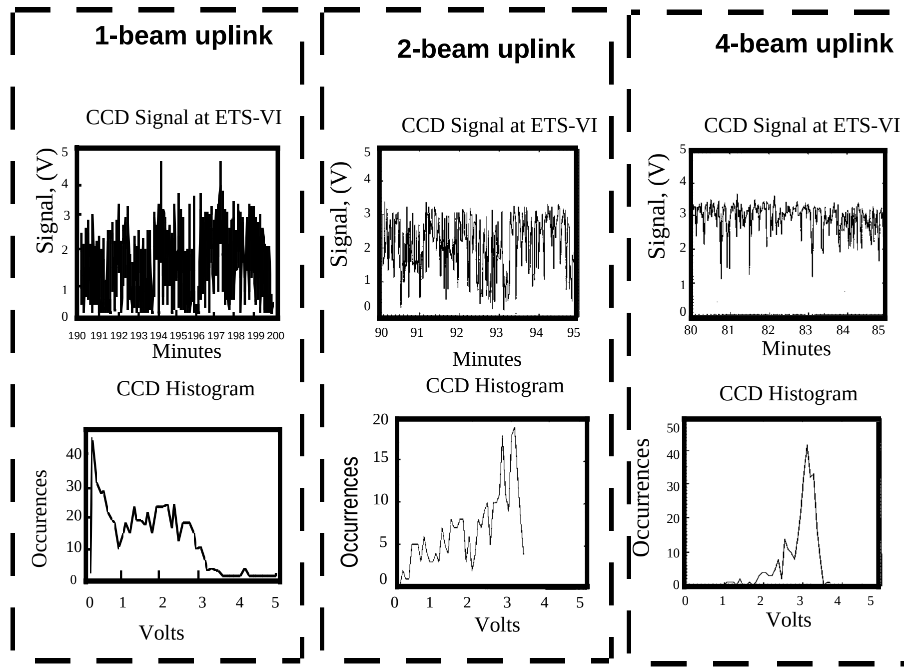
Past Opt. Comm. Demonstrations

GOLD Multiple-beam Transmission

- **Multiple beam uplink mitigates effects of atmospheric scintillation and beam wander**
  - **Beams are propagated through different atmospheric coherent cells**
  - **Each beam is delayed relative to the other by greater than laser's coherence length**



TMF 0.6-m Transmitter Telescope



Principal of Operations

Acquisition → Locate beacon to within 1/2 pixel accuracy to start tracking

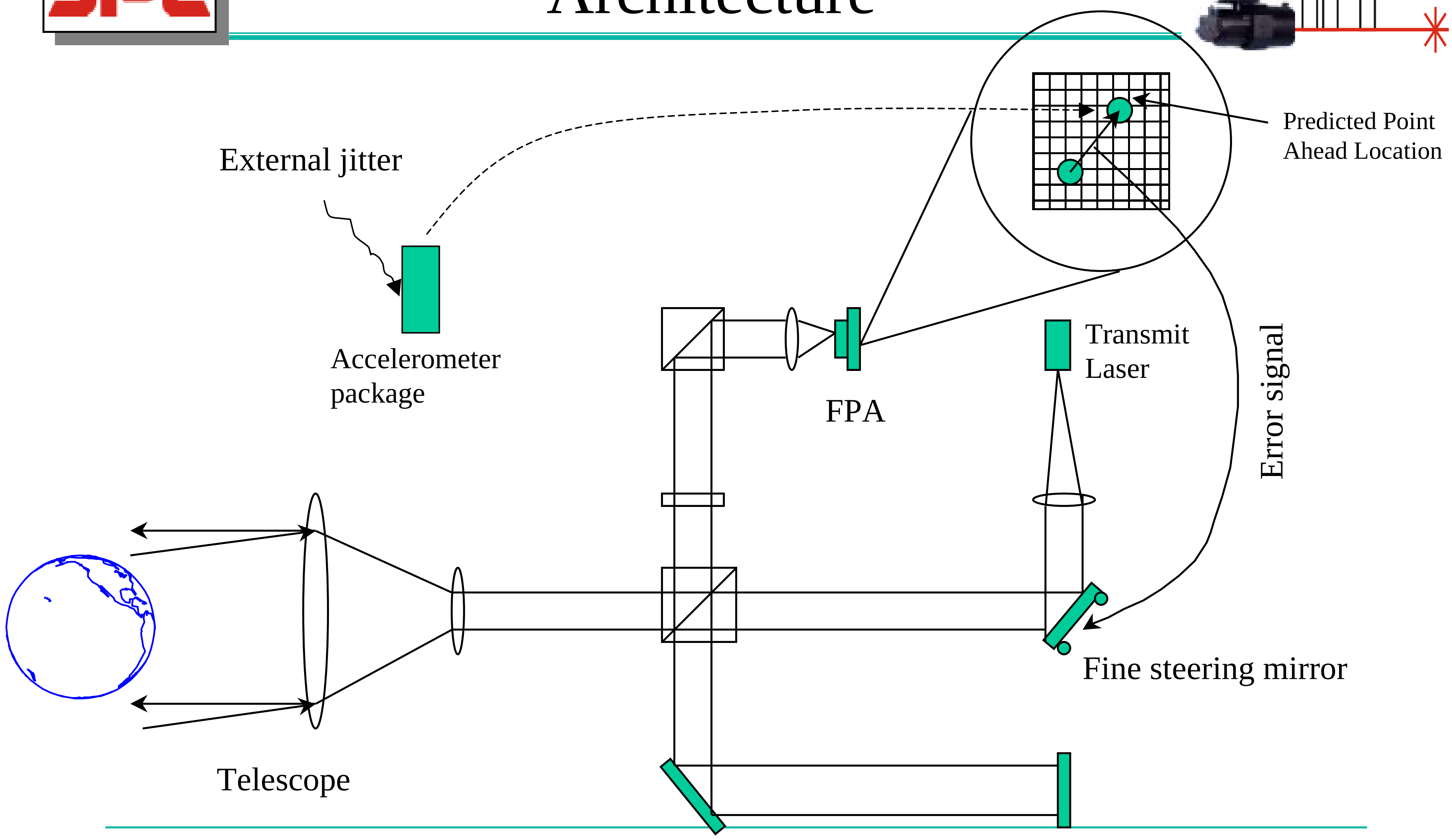
↓

Tracking → Locate receiver position with less than 1/10th pixel accuracy
Maintain(control) receiver position within rms error tolerance

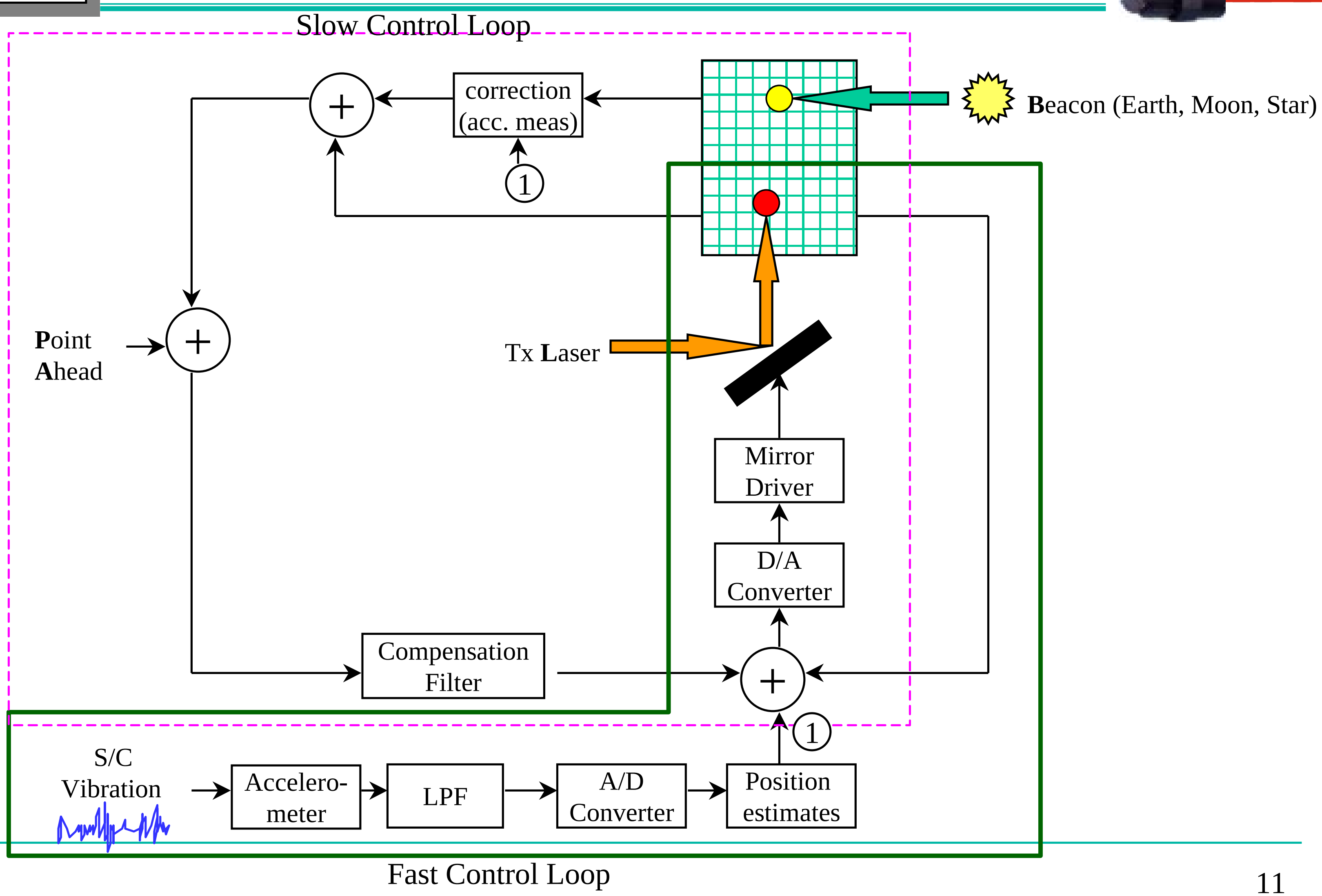
↓

Pointing → Transmit downlink beam to the derived direction with necessary accuracy
(ex. 3 sigma ~2μrad for Europa orbiter mission)

Acquisition/Tracking/Pointing Architecture



Acquisition/Tracking/Pointing Control Loop



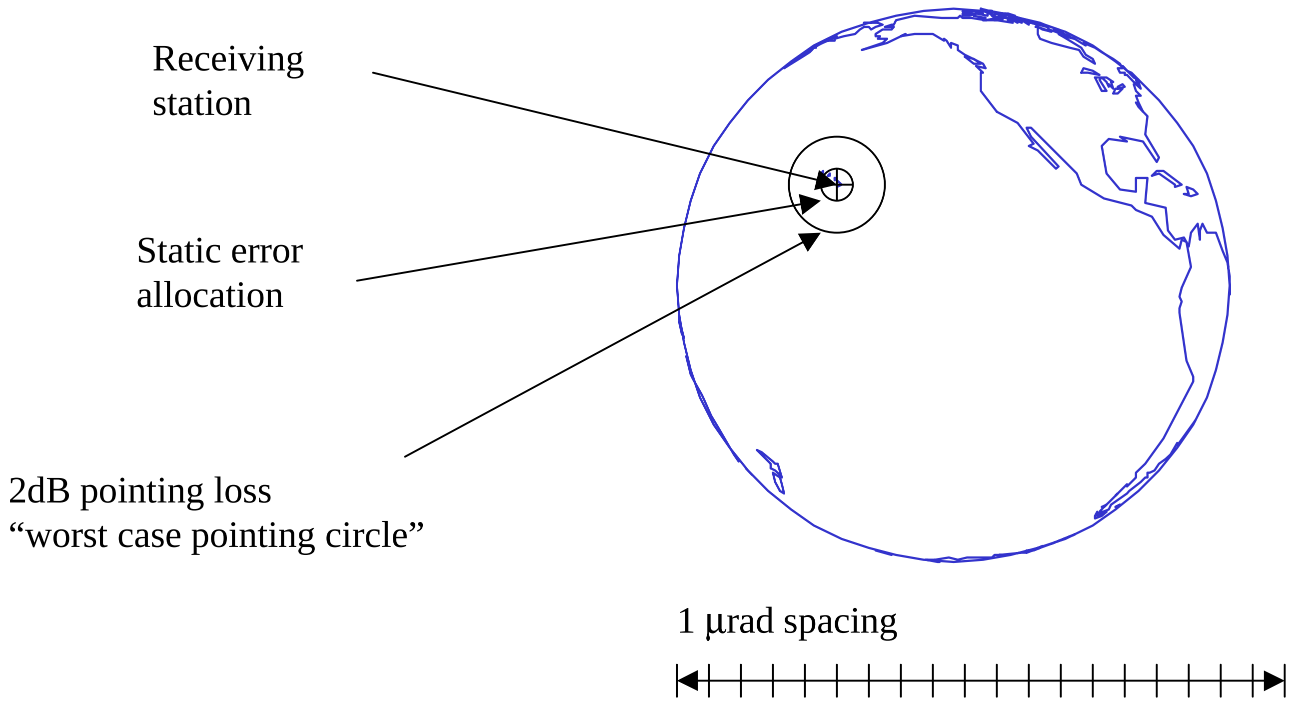
Sources of Tracking and Pointing Errors

- Total Pointing Error
  - Tracking
    - Control
      - Uncompensated S/C vibration
      - Accelerometer
    - Detector
      - NEA*
      - Spot size
      - Intensity distribution
  - Pointing
    - Pointing accuracy
      - Command resolution
      - detector
      - Point ahead error
    - Alignment

NEA* : Noise Equivalent Angle of tracking detector

Beam Pointing Requirements

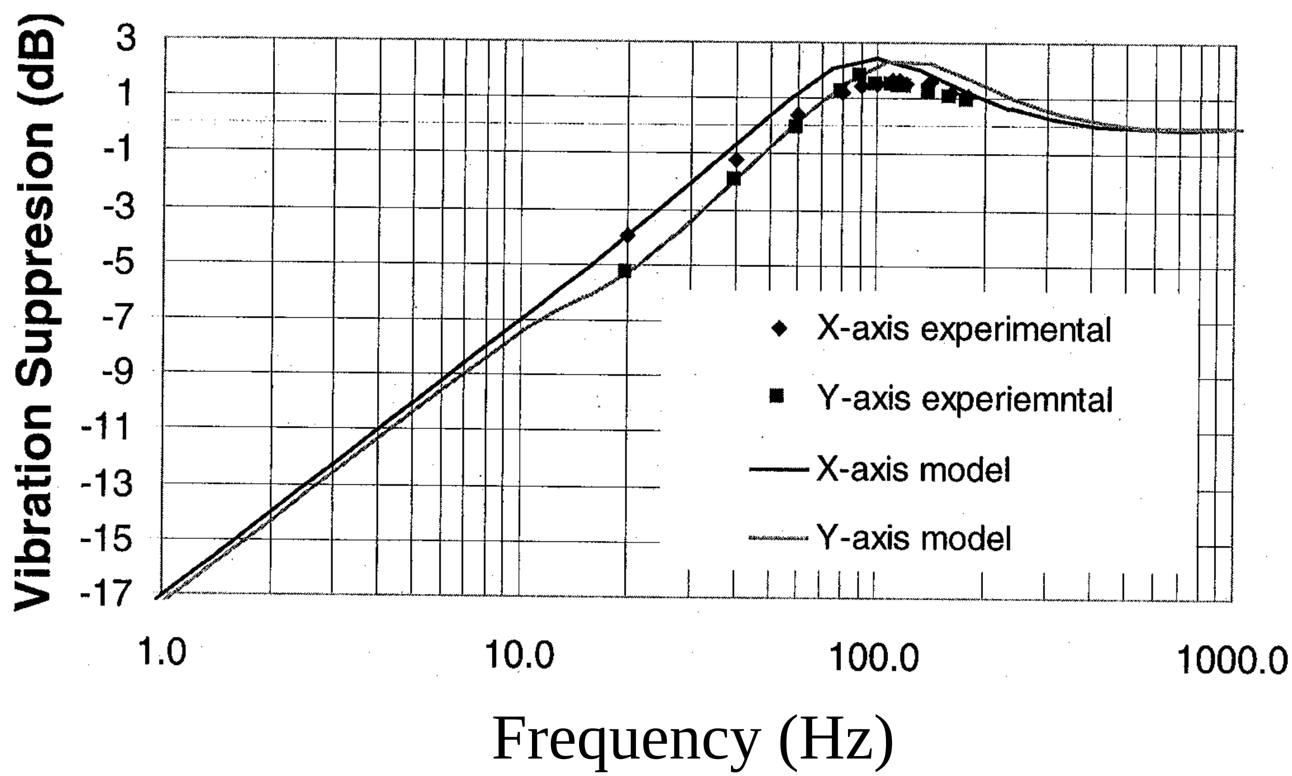
- Several µrad vs. 0.1 ~ 0.5 degrees (RF)



< Diagram illustrating the pointing requirements for the Europa orbiter mission>

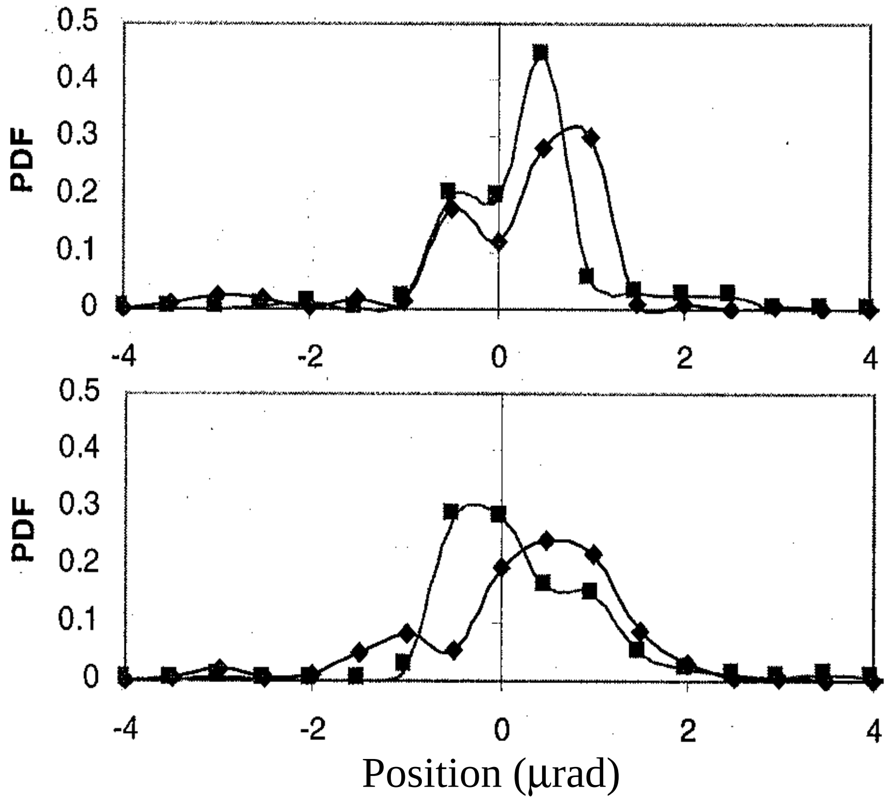
Lab OCD: Fine Tracking

- Vibration suppression bandwidth ~ 50Hz in both axes



Lab OCD: Centroiding Accuracy

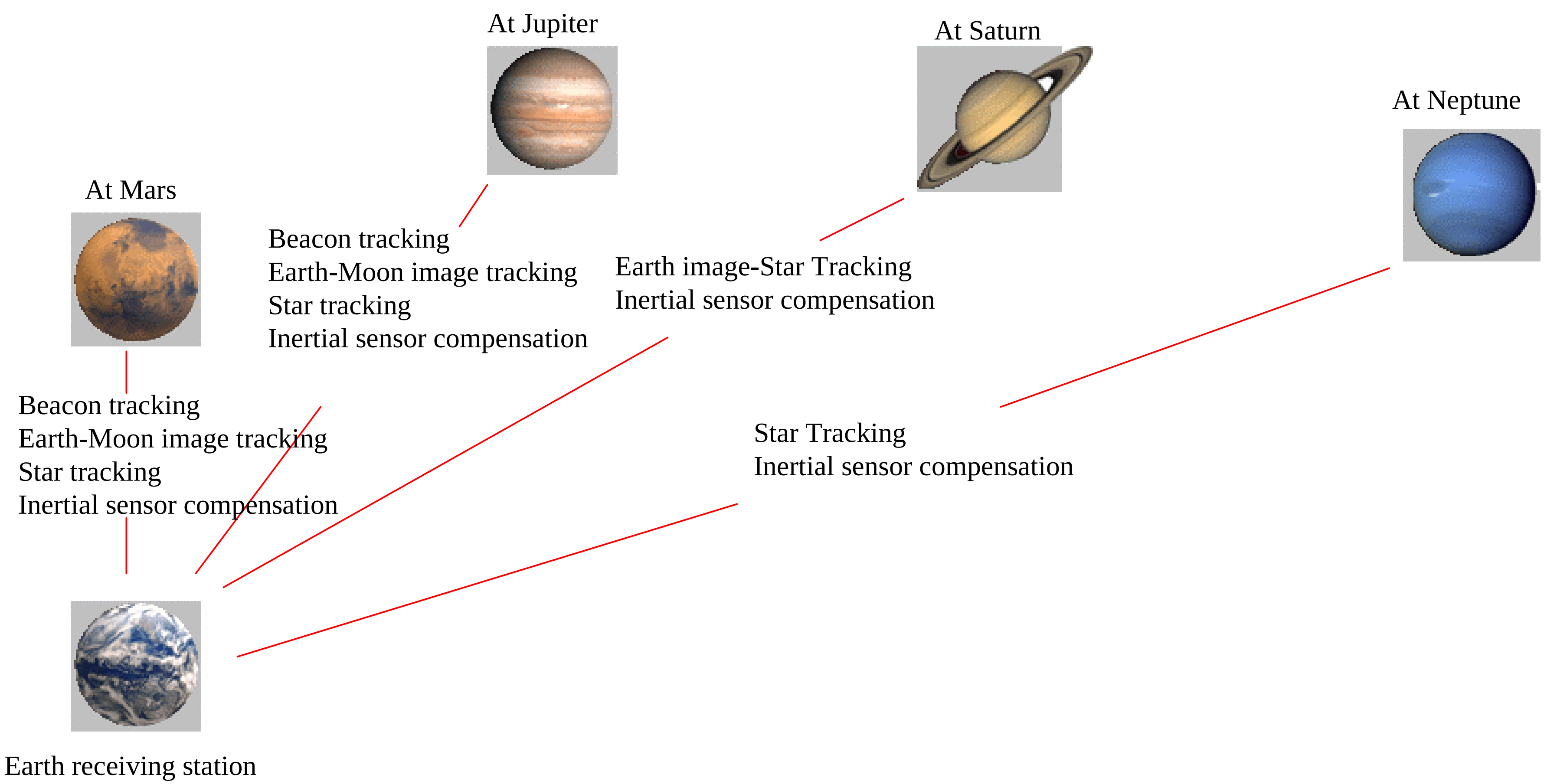
- Centroiding accuracy ~ one-tenth of a pixel



Laser/reference Centroid
$\sigma_x = 1.10\ \mu\text{rad}$
$\sigma_y = 1.10\ \mu\text{rad}$

Beacon Centroid
$\sigma_x = 1.12\ \mu\text{rad}$
$\sigma_y = 0.84\ \mu\text{rad}$

ATP Technologies for Deep Space Missions

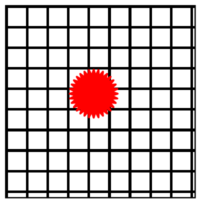


Approaches for Accurate Tracking/Pointing

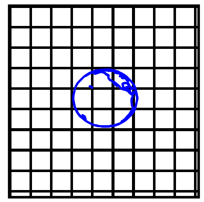
- S/C does not provide accurate receiver position
- Various sources (uplink laser, Earth, Moon, Star) may be used as beacon.
- Need advanced FPA (Focal Plane Array) with high QE (Quantum Efficiency) and large field of view
- Increase tracking bandwidth
- Decrease the transmission of S/C vibration
- Different ATP strategies are necessary to fully exploit various beacon sources

Comparison of Various Tracking Approaches

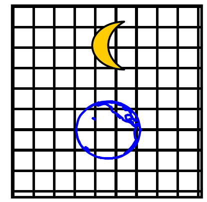
Uplink Beacon tracking



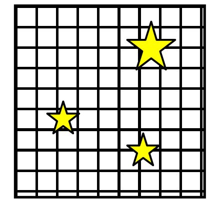
Earth tracking only



Earth-Moon tracking

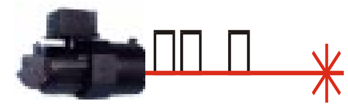


Star tracking only



	Uplink Beacon tracking	Earth tracking only	Earth-Moon tracking	Star tracking only
Req.'s	Uplink signal	calibration for albedo variations	predictable albedo Moon requires 40x integration time	FOV, inertial sensor, straylight rejection
Limitation	Only applicable at close w/o inertial sensor	Signal varies w/ distance, phase angle	Signal varies w/ distance, phase angle	Low signal 10-20Hz for 10^{th} mag. stars
S/C attitude for track	Yes	Yes	Yes	No
High Earth signal	No	Yes	Yes	No
Inertial sensors	Not near to Earth	@High phase angles	@High phase angles Long exposure (Moon)	Yes

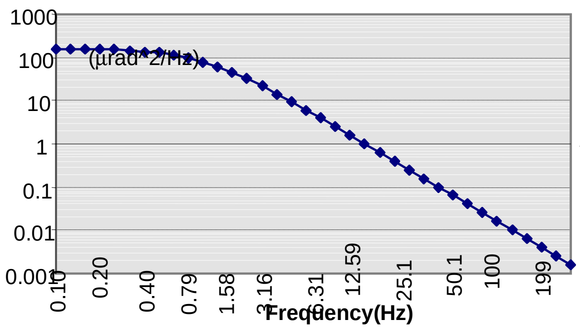
Key Technology Developments



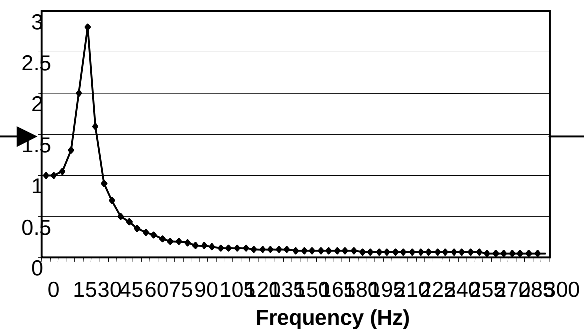
- **Vibration Isolation** - dominant source to mispointing, especially high frequency vibration
- **Inertial Sensor** - increases tracking bandwidth
- **Extended Source Image Acquisition Algorithm** - Earth, Moon images can be used as beacon source
- **Star Tracking** -stars are attractive beacon sources beyond 10AU
- **Fast Steering Mirror (FSM)** - increases tracking bandwidth
- **Focal Plane Array (FPA)** - determines pointing accuracy

Technology Developments - Vibration Isolation

- Passive isolator - cost effective and efficient method to improve tracking capability by reducing transmission of high frequency S/C vibration

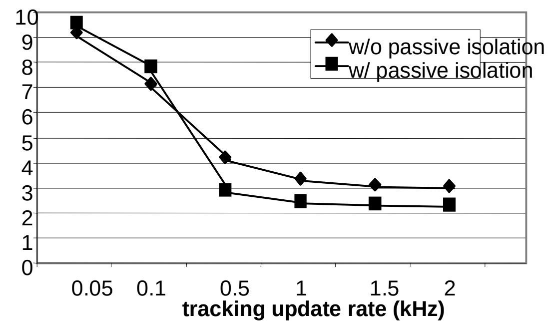


Olympus S/C vibration power spectral density



Passive isolator
Lord HTOP-5

OCD tracking system



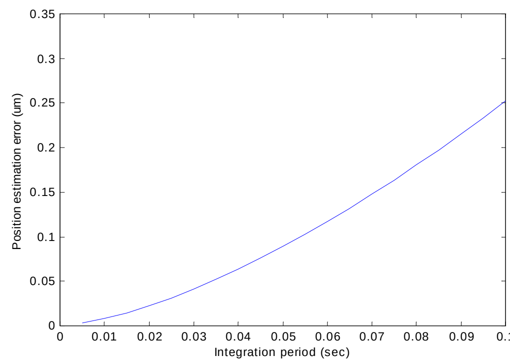
Uncompensated, S/C vibration induced tracking error

- Tracking error can be reduced by 20~30%

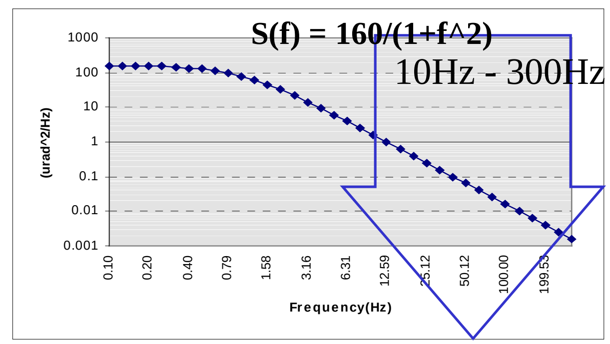
Technology Developments - Inertial sensor

- S/C vibration causes random disturbance along telescope bore-sight
- Weak beacon signal -> slow FPA update -> poor tracking capability
- Inertial sensor can compensate slow FPA update by measuring S/C vibration between FPA updates
- **Key parameters** - S/C position estimation error due to **sensor rms noise** & **calibration error**

Picture of QA-3000 accelerometer
rms noise - 76µg
calibration error - 0.5%



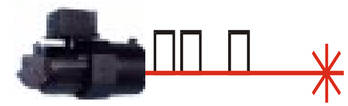
Position estimation error for rms noise of 100µg and sampling of 5kHz

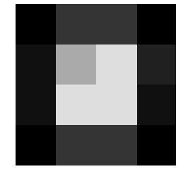


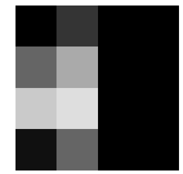
rms jitter of 4urad

Calibration error should be better than 2.5% for integration time of 0.1 sec. and error budget of 0.1µrad given Olympus S/C base motion PSD.

Technology Developments - Image acquisition







Estimation of receiver location from extended source

Estimation of geometric center of extended source

Known offset from receiver to geo-center

Acquisition algorithms - sensitive to albedo variations and background noise

- Correlation method
- Edge detection method

Albedo offset calibration - Moon or star image can be used to calibrate due to its known albedo or light intensity distributions

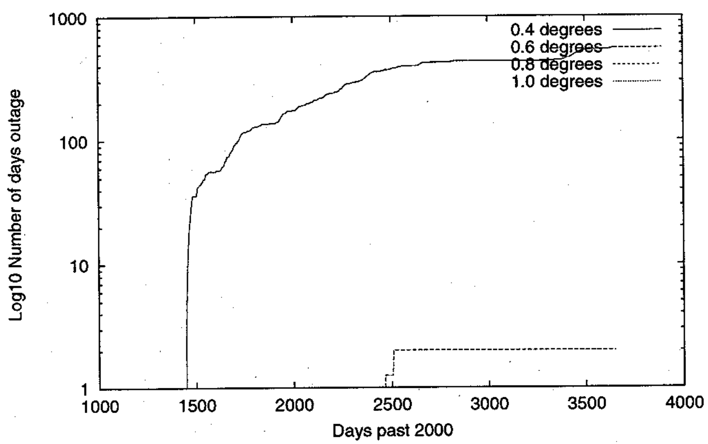
Accuracy improvements - Multiple, sequential images with edge detection yielded 1/40th pixel accuracy in simulations

Technology Developments - Star Tracking

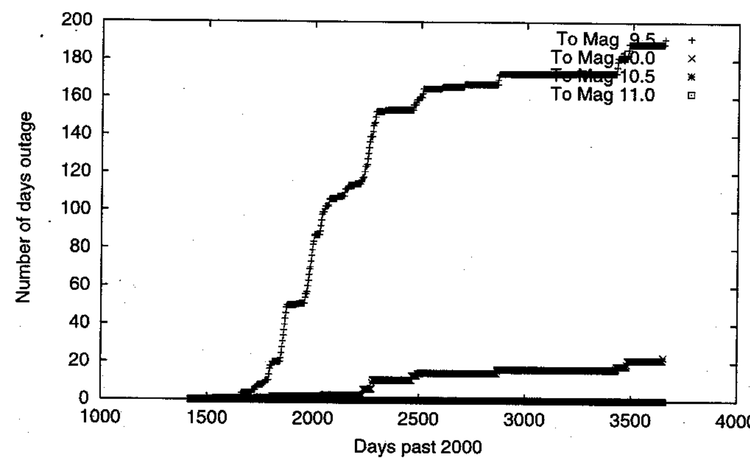
- Key parameters - signal level, star coverage

Star Magnitude	Flux with no optical loss (400 – 900nm)	Flux with 25% system efficiency	Number of frames/sec. For accurate centroiding
7.5	1.0E6	250,000	25 to 50
10.0	1.0E5	25,000	5 to 10
11.0	4.0E4	10,000	1 or 2

< Signal strength from stars of different magnitudes >



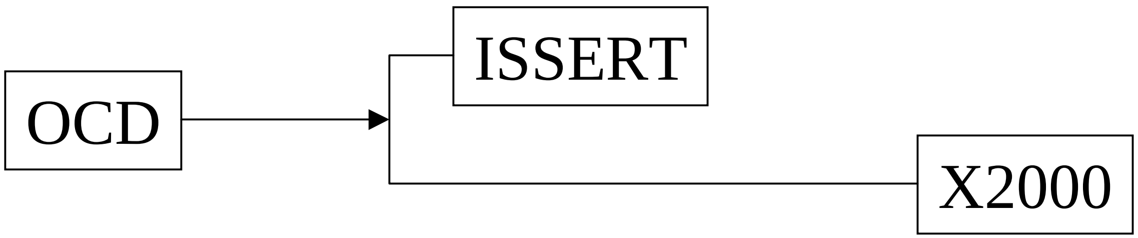
Number of days with less than 5 stars and a limiting magnitude of 11



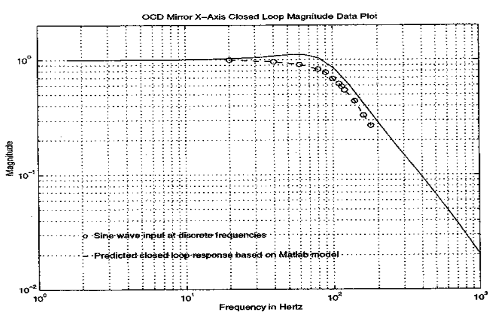
Number of days with less than 2 stars within 0.6 degrees of Earth as seen from Jupiter

Technology Developments - Fast Steering Mirror

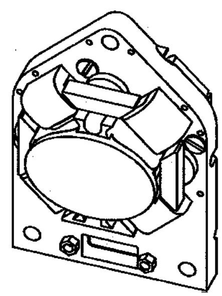
FSM determines vibration rejection capability of tracking control system



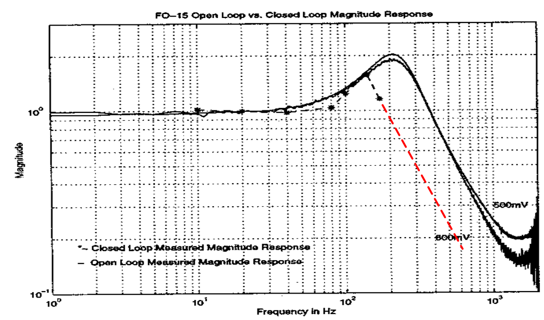
	General Scanning Tabs II mirror	LHD FO15 mirror
Travel	+-25mrad	+-44mrad
Resonance frequency	17/19Hz	205/270Hz



3dB @ 120Hz



FO15



3dB @ >200Hz

Technology Developments - Focal Plane Array

OCD → ISSERT → X2000

	OCD	ISSERT	X2000
Format	128x128	512x512	1024x1024
Pixel size	16μm	12μm	10-20μm
Bits/pixel	8bits	10bits	>12bits
Frame update rate	2kHz	2kHz	>500Hz
Centroiding accuracy	1/10th pixel	<1/10th pixel	< 1/20th pixel

Summary

- Narrow laser transmit beam imposes many technical challenges in beam pointing
- S/C vibration is the dominant source to beam mispointing
- Bright beacon signal (Uplink laser, Earth, Moon, Stars) is necessary to maintain receiver position within few μrad under S/C vibration
- Scattered sun light is a major consideration for dim beacon signal
- Various ATP strategies are required to successfully address the need for deep space optical communication